Ankudinov Ship Squat Predictions – Part I: Theory, Parameters, and FORTRAN Programs

by Michael J. Briggs

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) summarizes the Ankudinov empirical formula for ship squat predictions used by the U.S. Army Engineer Research and Development Center (ERDC) Ship Tow Simulator (STS). This CHETN documents the Ankudinov squat formulas and describes two FORTRAN programs that were written for single and multiple ship speed applications. Two examples are given for a Panamax bulk carrier and Panamax tanker for both programs. A companion CHETN compares and validates the Ankudinov squat predictions with laboratory measurements of a Post-Panamax containership and field measurements of a Panamax containership, tanker, and bulk carrier in the Panama Canal. It also compares the Ankudinov formula with several of the Permanent International Association of Navigation Congresses (PIANC) empirical squat formulas.

BACKGROUND: Squat is the reduction in underkeel clearance (UKC) between a vessel at-rest and underway due to the increased flow of water past the moving hull. The forward motion of the ship pushes water ahead of it that must return around the sides and under the keel. This water motion induces a relative velocity between the ship and the surrounding water that causes a water level depression in which the ship sinks. The velocity field produces a hydrodynamic pressure change along the ship similar to the Bernoulli effect. This phenomenon produces a downward vertical force (sinkage, positive downward) and a moment about the transverse axis (trim, positive bow up) that can result in different values of squat at the bow and stern (Figure 1). This combination of sinkage and change in trim is called ship squat.

The main ship parameters include:

- Ship draft or draught T
- Hull shape as represented by the block coefficient C_B
- Ship speed V_S (m/sec) or V_k (knots)

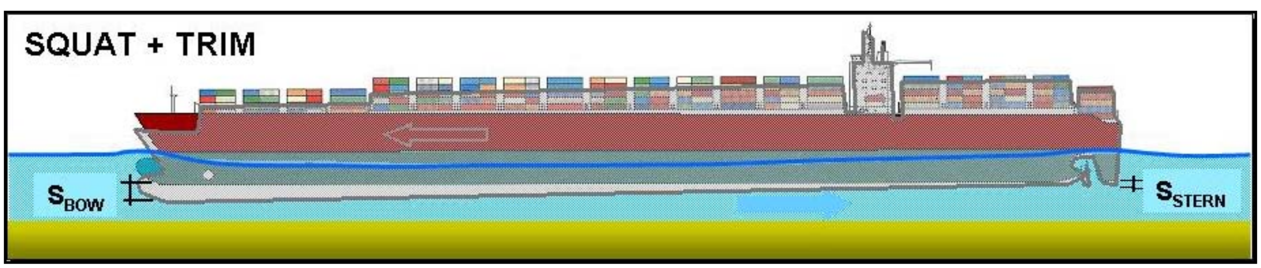

Figure 1. Schematic of ship squat at bow and stern (figure courtesy of Handbook of Coastal and Ocean Engineering, World Scientific Publishers).

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Other ship parameters include the length between forward and aft perpendiculars L_{pp} and the beam B. The C_B is a measure of the "fineness" of the vessel's shape relative to an equivalent rectangular volume with the same dimensions. The range of values of C_B is typically between 0.45 for high-speed vessels and 0.85 for slow, full-size tankers and bulk carriers. Typically, full-form ships like tankers and bulk carriers squat by (i.e., at) the bow S_b and more slender ships like containerships by the stern S_s. The initial trim of the ship also influences the location of the maximum squat. The most important ship parameter is its speed V_S. The main channel considerations are proximity of the channel sides and bottom and cross-sectional configuration. The three channel configurations are unrestricted or open or fairway (U), restricted or trench (R), and canal (C). Channel parameters include channel depth h, inverse side slope n (i.e., n = run/rise = cot θ), and trench height from the bottom of the channel to the top of the trench h_T. For a canal cross section, h_T equals h.

This CHETN builds on the earlier CHETN entitled "Ship Squat Predictions for Ship/Tow Simulator," CHETN-I-72 (Briggs 2006) that summarized several PIANC empirical ship squat predictions. The Ankudinov squat predictions are currently used in the Corps STS. In the first section, the equations are described for the Ankudinov ship squat predictions. In the next section, the FORTRAN programs *ANKUDINOV4* for single ship speed and *ANKUDINOVM4* for multiple ship speeds are described. An application of CHETN-I-63 (Demirbilek and Sargent 1999) and CHETN-I -72 (Briggs 2006), the Panamax bulk carrier is used to describe the input and output parameters and results from the Ankudinov predictions relative to PIANC (1997) empirical formulas for unrestricted (open) applications. Finally, in Engineer Manual (EM) 1110-2-1613 the Panamax tanker is used as an example to illustrate the effect of channel type on the Ankudinov predictions for bow squat. Part II of this CHETN will compare and validate the Ankudinov predictions with laboratory and field measurements for several ship and channel combinations.

ANKUDINOV SQUAT FORMULA: Ankudinov and Jakobsen (1996) and Ankudinov et al. (1996, 2000) proposed the MARSIM 2000 formula for maximum squat based on a midpoint sinkage Sm (SMid) and vessel trim Trim (Trim) in shallow water. The names in parenthesis correspond with the nomenclature used in the FORTRAN programs. Appendix A contains a list of all the parameters in the Ankudinov programs for ease of reference. The Ankudinov method has undergone considerable revision as new data were collected and compared. The most recent modifications from a study of ship squat in the St. Lawrence Seaway (Stocks et al. 2002), are e-mails and telecons in April 2009 (Ankudinov 2009) that are contained in this CHETN and the FORTRAN programs.

The Ankudinov prediction is one of the most thorough, but also the most complicated formulas for predicting ship squat. These components include factors to account for the effects of the ship and channel. The restriction on Depth Froude Number F_{nh} are values less than or equal to 0.6. The maximum ship squat S_{Max} (SMax) is a function of two main components: the midpoint sinkage S_m (SMid) and the vessel trim, *Trim* (Trim) given by:

$$S_{Max} = L_{pp}\left(S_m \mp 0.5 Trim\right) \tag{1}$$

The S_{Max} can be at the bow or stern depending on the value of *Trim*. The negative sign in Equation 1 is used for bow squat S_b (SbA) and the positive sign for stern squat S_s (SsA).

Midpoint Sinkage S_m (SMid). The S_m (SMid) is defined as:

$$S_m = SMid = \left(1 + K_P^S\right) P_{Hu} P_{F_{nh}} P_{+h/T} P_{Ch1} \tag{2}$$

The ship, water depth, and channel parameters in this midpoint sinkage equation are described in the following paragraphs. The *propeller parameter* K_P^S (KpS) is defined as:

$$K_P^S = KpS = \begin{cases} 0.15 & \text{single propeller} \\ 0.13 & \text{twin propellers} \end{cases} \tag{3}$$

The *ship hull parameter* for shallow water P_{Hu} (Par_Hull_s) was recently modified by Ankudinov (2009) as:

$$P_{Hu} = Par\_Hull\_s = 1.7 C_B \left(\frac{BT}{L_{pp}^2} \right) + 0.004 C_B^2 \tag{4}$$

The *ship forward speed parameter* P_{Fnh} (Par_Fnh) is given by:

$$P_{F_{nh}} = Par\_Fnh = F_{nh}^{(1.8 + 0.4 F_{nh})} \tag{5}$$

which is a numerical approximation to the term “$F_{nh}^2 \big/ \sqrt{1 - F_{nh}^2}$ ” that is in many of the PIANC empirical squat formulas. The F_{nh} (Fnh) is defined as:

$$F_{nh} = Fnh = \frac{V_s}{\sqrt{gh}} \tag{6}$$

The *water depth effects parameter* $P_{+h/T}$ (Par_hT_s) is defined as:

$$P_{+h/T} = Par\_hT\_s = 1.0 + \frac{0.35}{\left(h/T\right)^2} \tag{7}$$

Note that the h/T ratio corresponds to the nondimensional ratio R_{hT}.

The *channel effects parameter* P_{Ch1} (P_Ch1) is given by:

$$P_{Ch1} = P\_Ch1 = \begin{cases} 1.0 & \text{U} \\ 1.0 + 10 S_h - 1.5 \left(1.0 + S_h\right) \sqrt{S_h} & \text{R,C} \end{cases} \tag{8}$$

where the canal or restricted configuration is incorporated in the *channel depth factor* S_h (Sh) defined by:

$$S_h = Sh = C_B \left(\frac{S}{h/T} \right) \left(\frac{h_T}{h} \right) \qquad \text{R,C} \tag{9}$$

and the *blockage factor* S (= A_S/A_{Ch}) is the fraction of the cross-sectional area of the waterway A_{Ch} that is occupied by the ship's underwater midships cross section A_S.

Vessel *Trim*. The second main component in the MARSIM squat equation is the vessel trim, *Trim* that was also recently modified by Ankudinov (2009) as:

$$Trim = -1.7 P_{Hu} P_{F_{nh}} P_{h/T} K_{Tr} P_{Ch2} \tag{10}$$

Note that the L_{pp}/B ratio corresponds to the nondimensional ratio R_{LB}. In addition to the three parameters already described for the midpoint sinkage equation, the *Trim* also includes parameter $P_{h/T}$ (Par_hT) and coefficient K_{Tr} (KTr) to quantify the effects of the ship propellers, bulbous bow, stern transom, and initial trim.

The *vessel trim parameter* $P_{h/T}$ (Par_hT) accounts for the reduction in trim due to the propeller in shallow water and is defined as:

$$P_{h/T} = Par\_hT = 1 - e^{\left[\frac{2.5(1-h/T)}{F_{nh}} \right]} \tag{11}$$

The *Trim coefficient* K_{Tr} (K_Tr) is a function of many factors and is given by:

$$K_{Tr} = K\_Tr = C_B^{nTr} - \left(0.15 K_P^S + K_P^T \right) - \left(K_B^T + K_{Tr}^T + K_{T1}^T \right) \tag{12}$$

The first factor in this equation C_B^{nTr} is the block coefficient C_B, raised to the n_{Tr} (nTr) power. This *Trim exponent* n_{Tr} is defined as:

$$n_{Tr} = nTr = 2.0 + 0.8 \frac{P_{Ch1}}{C_B} \tag{13}$$

The next two factors define the propeller effect on the vessel trim. The first factor K_P^S (KpS) is the same as the *propeller parameter* for the midpoint sinkage and the second factor is the *propeller trim parameter* K_B^T (KpT):

$$K_P^T = KpT = \begin{cases} 0.15 & \text{single propeller} \\ 0.20 & \text{twin propellers} \end{cases} \tag{14}$$

The last group of three factors define the effects of the bulbous bow K_b^T (KbT), stern transom K_{Tr}^T (KTrT), and initial trim K_{T1}^T (KT1T) on the vessel trim. The *bulbous bow factor* K_b^T (KbT) is given by:

$$K_b^T = KbT = \begin{cases} 0.1 & \text{bulbous bow} \\ 0.0 & \text{no bulbous bow} \end{cases} \tag{15}$$

The *Stern transom factor* K_{Tr}^T (KTrT) is defined by:

$$K_{Tr}^T = KTrT = \begin{cases} 0.1\left[\dfrac{B_{Tr}}{B}\right] = 0.1\left[\dfrac{0.4B}{B}\right] = 0.04 & \text{stern transom} \\ 0.0 & \text{no stern transom} \end{cases} \tag{16}$$

where B_{Tr} (BTr) is the *Stern transom width* and is typically 0.4 B, although values as high as 0.7 B have sometimes been used.

The *initial trim effect factor* K_{T1}^T (KT1T) is given by:

$$K_{T1}^T = KT1T = \frac{\left(T_{ap} - T_{fp}\right)}{\left(T_{ap} + T_{fp}\right)} \tag{17}$$

where T_{ap} (Tap) is the static draft at the stern or aft perpendicular and T_{fp} (Tfp) is the static draft at the bow or forward perpendicular.

Finally, the *channel effect trim correction parameter* (Par_Ch2) P_{Ch2} is defined as:

$$P_{Ch2} = Par\_Ch2 = \begin{cases} 1.0 & \text{U} \\ 1.0 - 5S_h & \text{R,C} \end{cases} \tag{18}$$

FORTRAN PROGRAMS *ANKUDINOV4* and *ANKUDINOVM4*: The two FORTRAN programs ANKUDINOV4 and ANKUDINOVM4 are similar to each other as the one with the "M" in the name (for multiple ship speeds) is a copy of the other for single ship speeds. They both reflect the latest Version 3 modifications. The multiple speed version can have any beginning, increment, and number of speeds as long as not greater than 100. In 2000, both programs were written in Compaq Visual Fortran, Version 6.5. They are similar to the program SQUAT for the PIANC formulas described in CHETN-I-72 (Briggs 2006). They are modular as most components are contained in separate subroutines. The user can enter input data in two different ways: in manual entry mode (Subroutine Input) or by reading (Subroutine ReadIn) a previously stored file of the input variables. Both are performed in real time, but the ReadIn option is more efficient as the user does not have to re-enter input for each run. Input data are automatically stored (Subroutine Store) in a generic input file AnkudIn.out (AnkudMIn.out for ANKUDINOVM4) after input is completed. The output is stored in a generic file named AnkudOut.out (AnkudMOut.out for ANKUDINOVM4). The user can (and should) rename these generic input and output files to save the data for later use and analysis.

The program is well documented with comments throughout. The naming convention follows the PIANC (1997) and Ankudinov et al. (1996, 2000) nomenclature. Units are in the metric system with predicted squat in meters. The program is completely stand-alone at this point so that it can

be used in comparisons with other squat predictions (see CHETN-I-72). Interested readers can obtain a copy of the executable version of the program and I/O files by contacting the author.

Input. The first input question is whether the user wants to manually input (enter **I**) or read in (enter **R**) the data from a previously stored file. The next question is the type of channel. The user can enter **U** for unrestricted, **R** for restricted, or **C** for canal. The input is the same for all three channel configurations for most of the questions, but each has some slight variations. These first two inputs are all in capital letters. If the user accidentally enters in small letters, the program will abort. The user must then restart (**CNTL C** keys together to cancel the open DOS window) and re-enter the input values in capital letters.

The next questions involve the ship and channel parameters. Table 1 lists input parameters, symbols, and units for both programs for all three channel configurations. Figure 2 is an example for an unrestricted channel (U) for (a) ANKUDINOV4 and (b) ANKUDINOVM4 programs using the **R** (i.e., ReadIn option). This example is for the modified *Bunga Saga Emphat* Panamax bulk carrier that was originally described by Harkins and Dorrell (2000) and used in CETN-I-63 and CHETN-I-72. Table 2 summarizes the input parameters for this example as well as the R and C channel types. After completing input, the program runs without any further action from the user.

Table 1. ANKUDINOV4 and ANKUDINOVM4 input parameters.

Parameter Description	Symbol	Units	Program	Channel Type		
				Unrestricted U	Restricted R	Canal C
Length between perpendiculars	L_{pp}	m	Both	Y	Y	Y
Beam	B	m	Both	Y	Y	Y
Draft	T	m	Both	Y	Y	Y
Draft at forward perpendicular	T_{fp}	m	Both	Y	Y	Y
Draft at aft perpendicular	T_{ap}	m	Both	Y	Y	Y
Block coefficient	C_B	---	Both	Y	Y	Y
Vessel speed or 1st speed	V_k	knots	ANKM	Y	Y	Y
Vessel increment speed	V_{Inc}	knots	ANKM	Y	Y	Y
Number of speeds	NVel	---	ANKM	Y	Y	Y
Number propeller flag	IProp	---	Both	Y	Y	Y
Bulbous bow flag	IBow	---	Both	Y	Y	Y
Transom stern flag	IStern	---	Both	Y	Y	Y
Channel width at bottom	W	m	Both	N	Y	Y
Bank slope (inverse)	n	---	Both	N	Y	Y
Height dredged underwater trench	h_T	m	Both	N	Y	N

Notes:
1. Both = Both Programs ANKUDINOV4 and ANKUDINOVM4.
2. ANKM = Program ANKUDINOVM4 only.
3. N = No, Y = Yes.

```
   251.1600                                                    ! Vessel length between perpendiculars Lpp, m
    32.2500                                                    ! Vessel beam B, m
    12.8000                                                    ! Vessel draft T, m
    12.8000                                                    ! Vessel draft TFp, m
    12.8000                                                    ! Vessel draft TAp, m
     0.9050                                                    ! Vessel block coefficient CB
    10.0000                                                    ! Vessel speed Vk, kts
    15.3600                                                    ! Water depth h, m
     1                                                         ! Single (1) or twin (2) propeller, IProp
     1                                                         ! Bulbous bow (1) or conventional (0), IBow
     0                                                         ! Stern transom (1) or conventional (0), IStern
Panamax Bulk Carrier, CETN-I-63, Mar 99, Demirbilek & Sargent
Unrestricted Channel, Ankudinov4 - 29Apr09 Changes, 29Apr09
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```
   251.1600                                                    ! Vessel length between perpendiculars Lpp, m
    32.2500                                                    ! Vessel beam B, m
    12.8000                                                    ! Vessel draft T, m
    12.8000                                                    ! Vessel draft TFp, m
    12.8000                                                    ! Vessel draft TAp, m
     0.9050                                                    ! Vessel block coefficient CB
     5.0000                                                    ! Vessel speed Vk, kts
     1.0000                                                    ! Vessel increment speed VInc, kts
    11.0000                                                    ! Number vessel speeds NVel
    15.3600                                                    ! Water depth h, m
     1                                                         ! Single (1) or twin (2) propeller, IProp
     1                                                         ! Bulbous bow (1) or conventional (0), IBow
     0                                                         ! Stern transom (1) or conventional (0), IStern
Panamax Bulk Carrier, CETN-I-63, Mar 99, Demirbilek & Sargent
Unrestricted Channel, AnkudinovM4 - 29Apr09 Changes, 29Apr09
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Figure 2. Example generic input files for modified *Bunga Saga Emphat* Panamax bulk carrier and unrestricted channel for (a) single ship speed AnkudIn.out and (b) multiple ship speeds AnkudMIn.out.

Table 2. Ship and channel input parameters for modified *Bunga Saga Emphat* Panamax bulk carrier.

L_{pp} (m)	B (m)	T (m)	C_B	h (m)	h_T (m)	W (m)	n
251.2	32.3	12.8	0.91	15.4	3.84	281	3

Notes:
1. Tfp = Tap = T; IProp = 1; IBow = 1; IStern = 0; KpS = 0.15; KpT = 0.15.

Output. The output is first printed to the screen in a DOS Window for the user to check. The user can examine the contents as long as necessary. A carriage return will close this window. The output is then automatically written to the generic output file AnkudOut.out (AnkudMOut.out for ANKUDINOVM4).

Figures 3a and b show the output corresponding to the inputs in Figure 2 for ANKUDINOV4 and ANKUDINOVM4, respectively. The project title, ship input parameters, channel input parameters, and calculated parameters are identical for both programs. The output parameters consisting of ratios and constants and the Ankudinov output parameters that include K factors and constants, Par factors and constants, and sinkage and trim results are next printed. The main difference between the programs is that the parameters that are affected by ship speed are listed separately as a function of speed. Also, the n_{Tr} trim exponent is not included for the multiple speed version.

Results. Figure 4 is a plot of the Ankudinov bow S_b (SbA) and stern S_s (SsA) squat predictions for the modified *Bunga Saga Emphat* bulk carrier in an unrestricted channel. Averages from the PIANC empirical formulas (CHETN-I-72) are also shown for reference. Table 3 lists the predicted values in meters for the Ankudinov programs at 5 and 10 knots for all three channel types U, R, and C. The non-dimensional ratio of the Ankudinov to PIANC predictions at bow and stern are also included for comparisons.

```
Results From Program Ankudinov4, Version 4.0
Panamax Bulk Carrier, CETN-I-63, Mar 99, Demirbilek & Sargent
Unrestricted Channel, Ankudinov4 - 29Apr09 Changes, 29Apr09

User accepts Waiver of Warranty, Limitation of Liability, Indemnity, and Assent
contained in the ReadMe file for Program Ankudinov4 and its versions


        *** Ship Input Parameters ***
        Length between perpendiculars, Lpp =        251.16 m
        Beam, B =                                    32.25 m
        Draft, T =                                   12.80 m
        Draft Forward Perpendicular, Tfp =           12.80 m
        Draft Aft Perpendicular, Tap =               12.80 m
        Block coefficient, CB =                      0.905

        *** Channel Input Parameters ***
        Channel type code CHType =                       U
        C = Canal
        R = Restricted Channel w/trench
        U = Unrestricted Channel or flat
        Water depth, h =                             15.36 m
        Channel effective width, WEff3 =            247.14 m
        Used for channel width

        *** Calculated Parameters ***
        Ship displacement volume, Vol =           93829.36 m^3
        Coef for As bilge radius, Cs =                0.98
        Area ship midship, As =                     404.54 m^2
        Area channel or canal, ACh =               3796.14 m^2
        Blockage factor, S =                         0.107

        *** Output Parameters ***
        Ratios and Constraints
        Block coefficient, CB =                      0.905
        Ship speed, Vk =                             10.00 kts
        Ship speed, Vs =                              5.14 m/s
        Depth Froude No., Fnh =                      0.419
        Ratio depth to draft, RhT=h/T =               1.20
        Ratio ship length to depth, RLh=Lpp/h =      16.35
        Ratio ship length to beam, RLB=Lpp/B =        7.79
        Ratio ship length to draft, RLT=Lpp/T =      19.62
        Ratio ship beam to draft, RBT=B/T =           2.52

        *** Ankudinov Output Parameters ***
        K Factors and Constants
        Single/Twin Propeller sinkage, KpS =          0.15
        Channel factor, Sh =                         0.080
        Channel effect, P_Ch1 =                      1.000
        Channel trim effect, P_Ch2 =                 1.000
        Trim exponent, nTr =                          2.88
        Single/Twin Propeller trim, KpT =             0.15
        Bulbous Bow trim, KbT =                       0.10
        Stern transom trim, KTrT =                    0.00
        Initial trim, KT1t =                          0.00
        Trim coefficient, K_Tr =                     0.477

        Par Factors and Constants
        Hull effect shallow, Par_Hull_s =           0.0133
        Water depth effect, Par_hT_s =              1.2431
        Forward speed effect, Par_Fnh =             0.1806
        Propeller effect shallow, Par_hT =          0.6967

        Sinkage & Trim Results
        Mid-ship sinkage, SMid =                   0.00345 m/m
        Ship Trim, Trim =                         -0.00136 m/m
        Bow Squat, SbA =                              1.04 m
        Stern Squat, SsA =                            0.69 m
```

Figure 3a. Example generic output files for modified *Bunga Saga Emphat* Panamax bulk carrier and unrestricted channel for single ship speed AnkudOut.out.

```
Results From Program AnkudinovM4, Version 4.0
Panamax Bulk Carrier, CETN-I-63, Mar 99, Demirbilek & Sargent
Unrestricted Channel, AnkudinovM4 - 29Apr09 Changes, 29Apr09

User accepts Waiver of Warranty, Limitation of Liability, Indemnity, and Assent
contained in the ReadMe file for Program AnkudinovM4 and its versions


        *** Ship Input Parameters ***
        Length between perpendiculars, Lpp =        251.16 m
        Beam, B =                                    32.25 m
        Draft, T =                                   12.80 m
        Draft Forward Perpendicular, Tfp =           12.80 m
        Draft Aft Perpendicular, Tap =               12.80 m
        Block coefficient, CB =                      0.905

        *** Channel Input Parameters ***
        Channel type code CHType =                       U
        C = Canal
        R = Restricted Channel w/trench
        U = Unrestricted Channel or flat
        Water depth, h =                             15.36 m
        Channel effective width, WEff3 =            247.14 m
        Used for channel width

        *** Calculated Parameters ***
        Ship displacement volume, Vol =           93829.36 m^3
        Coef for As bilge radius, Cs =               0.98
        Area ship midship, As =                     404.54 m^2
        Area channel or canal, ACh =               3796.14 m^2
        Blockage factor, S =                         0.107

        *** Output Parameters ***
        Ratios and Constraints
        Ratio depth to draft, RhT=h/T =               1.20
        Ratio ship length to depth, RLh=Lpp/h =      16.35
        Ratio ship length to beam, RLB=Lpp/B =        7.79
        Ratio ship length to draft, RLT=Lpp/T =      19.62
        Ratio ship beam to draft, RBT=B/T =           2.52

        *** Ankudinov Output Parameters ***
        K Factors and Constants
        Single/Twin Propeller sinkage, KpS =          0.15
        Channel factor effect, Sh =                  0.080
        Channel effect, P_Ch1 =                      1.000
        Channel trim effect, P_Ch2 =                 1.000
        Single/Twin Propeller trim, KpT =             0.15
        Bulbous Bow trim, KbT =                       0.10
        Stern transom trim, KTrT =                    0.00
        Initial trim, KT1T =                          0.00
        Trim coefficient, K_Tr =                     0.477
        Par Factors and Constants
        Hull effect shallow, Par_Hull_s =           0.0133
        Water depth effect, Par_hT_s =              1.2431


        *** Sinkage & Trim Results ***
   Speed       Fnh    Par_   Par_    SMid     Trim    SbA    SsA
 kts    mps    No.    Fnh     hT     (m/m)    (m/m)   (m)    (m)

  5.00  2.57  0.21   0.05   0.91   0.0010 -0.0005  0.32   0.19
  6.00  3.09  0.25   0.07   0.86   0.0014 -0.0007  0.43   0.26
  7.00  3.60  0.29   0.10   0.82   0.0018 -0.0008  0.56   0.35
  8.00  4.12  0.34   0.12   0.77   0.0023 -0.0010  0.71   0.45
  9.00  4.63  0.38   0.15   0.73   0.0028 -0.0012  0.86   0.57
 10.00  5.14  0.42   0.18   0.70   0.0034 -0.0014  1.04   0.69
 11.00  5.66  0.46   0.22   0.66   0.0041 -0.0015  1.22   0.84
 12.00  6.17  0.50   0.25   0.63   0.0048 -0.0017  1.43   0.99
 13.00  6.69  0.54   0.29   0.60   0.0056 -0.0019  1.65   1.17
 14.00  7.20  0.59   0.34   0.57   0.0064 -0.0021  1.88   1.36
 15.00  7.72  0.63   0.39   0.55   0.0074 -0.0023  2.14   1.56
```

Figure 3b. Example generic output files for modified *Bunga Saga Emphat* Panamax bulk carrier and unrestricted channel for multiple ship speeds AnkudMOut.out.

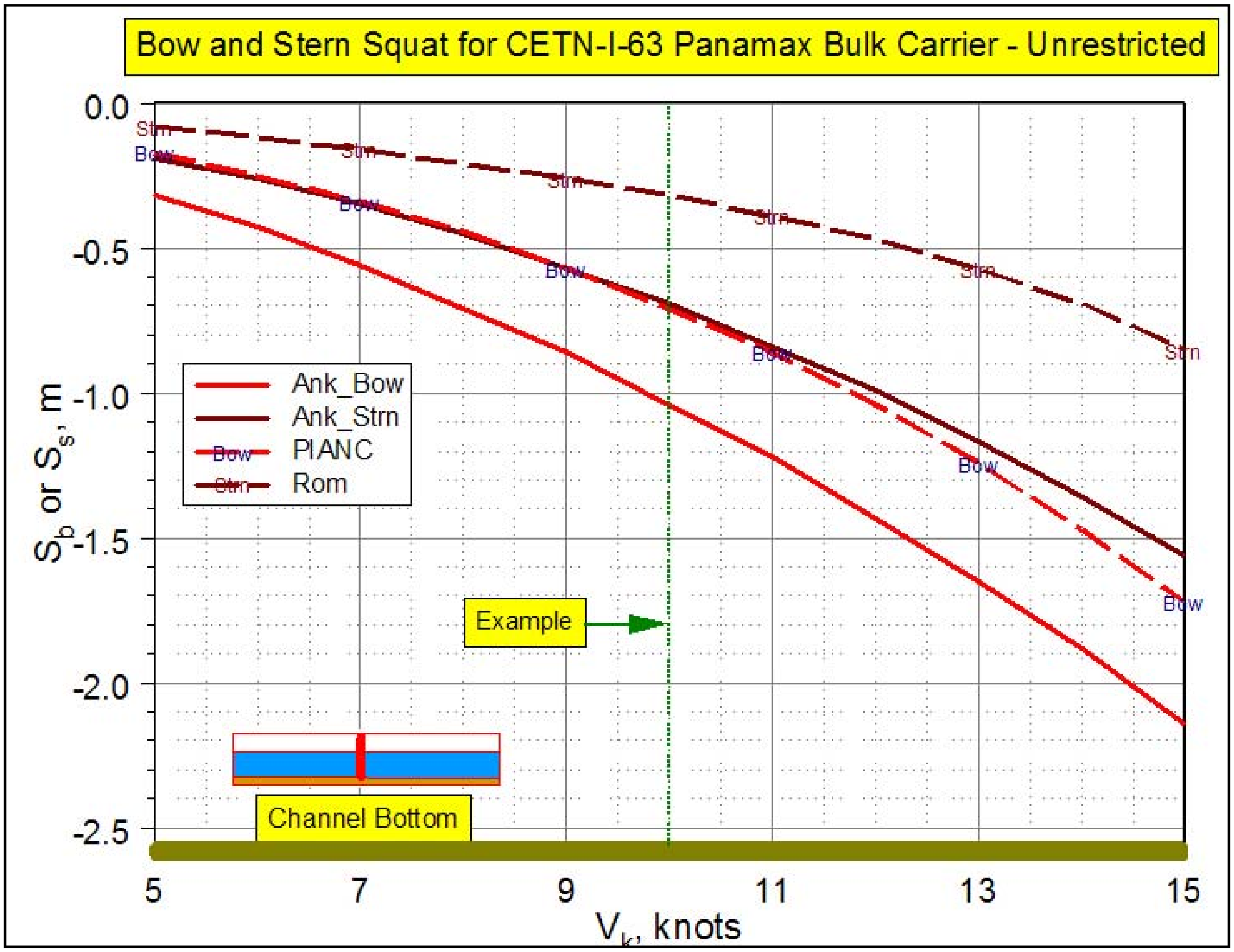

Figure 4. Ankudinov bow and stern squat predictions for modified *Bunga Saga Emphat* Panamax bulk carrier in unrestricted channel.

Table 3. ANKUDINOV4 and ANKUDINOVM4 bow and stern squat predictions for modified *Bunga Saga Emphat* Panamax bulk carrier.

Location	Channel Type					
	Unrestricted U		Restricted R		Canal C	
	5 knots	10 knots	5 knots	10 knots	5 knots	10 knots
Ankudinov Predictions (m)						
Bow	0.32	1.04	0.30	0.99	0.35	1.17
Stern	0.19	0.69	0.18	0.68	0.26	0.94
Ratio: Ankudinov/PIANC						
Bow	1.9	1.5	1.9	1.5	1.8	1.5
Stern	2.4	2.2	2.0	1.9	2.0	1.8

The modified *Bunga Saga Emphat* bulk carrier is a “blocky” ship (i.e., large C_B) that will squat by the bow. The Ankudinov predictions are on the conservative side, with overpredictions approximately 2 times (range between 1.5 and 2.4) those of other PIANC empirical formulas. In general, the Ankudinov bow predictions decreased as the ship velocity increased. The stern pre-

dictions also decreased as speed increased, but not as much as the bow predictions. Bow predictions are generally better (closer to PIANC predictions) than the stern predictions, which is good since this is the most significant squat value for this type of ship. The bow predictions ranged from 1.5 to 1.9 times the PIANC values compared to 1.8 to 2.4 multipliers for the stern predictions. Both bow and stern predictions increased for the C channel type relative to the U channel, as one would expect. The squat for the R channel tended to decrease slightly or stay the same relative to the U channel. This is probably due to the fact that the trench height was only 25 percent of the water depth and the side slope was relatively mild for such a wide channel.

Table 4 summarizes the minimum, average, and maximum ratios for the three channel types for the range of speeds from 5 to 15 knots. For bow squat, the average ratio overpredictions are 1.5 for all three channel types. Similarly for stern squat, the average squat ratios show overpredictions of 2.1, 1.8, and 1.6 for U, R, and C channels, respectively. Thus, the average Ankudinov predictions range from 1.5 to 2 times larger than the PIANC predictions for bow and stern squat. In summary, this comparison with PIANC empirical formulas is only intended to show the relative values of the Ankudinov predictions to the accepted PIANC standards. Of course, the PIANC values are also only predictions and not measurements. The companion Part II of this CHETN will present comparisons and validations with laboratory and field measurements for a range of ship and channel types.

Table 4. Statistical ratios of Ankudinov to PIANC bow and stern squat predictions for modified *Bunga Saga Emphat* Panamax bulk carrier.

Statistic	Channel Type					
	Unrestricted U		Restricted R		Canal C	
	Bow	Stern	Bow	Stern	Bow	Stern
Minimum	1.2	1.8	1.2	1.4	1.1	0.7
Average	1.5	2.1	1.5	1.8	1.5	1.6
Maximum	1.9	2.4	2.4	2.0	1.8	2.0

Notes:
1. PIANC Bow squat averages based on 12, 7, and 6 values for U, R, and C, respectively.
2. PIANC Stern squat averages based on 1 value (Römisch) for all three channel types.
3. Eleven ship speeds from 5 to 15 knots in 1 knot increments for all statistics.

EXAMPLE 2: A second example is included of the Panamax tanker in EM 1110-2-1613 (Headquarters, U.S. Army Corps of Engineers 2006). Table 5 lists the ship and channel properties for this example for all three channel types. The h/T = 1.1 for this example, so it has a relatively shallow UKC. This ship will squat more by the bow since $C_B \geq 0.7$. Figure 5 compares the Ankudinov predictions for bow squat for the three channel types with those of PIANC's Huuska formula from the EM 1110-2-1613 manual. Table 6 lists the minimum, average, and maximum ratios of Ankudinov to Huuska bow squat for the three channel types. These comparisons with the PIANC Huuska predictions are closer than the first example with a range of ratios of 0.9 to 2.0 for all three channel types. The Ankudinov predictions are the most similar to the Huuska predictions for the canal configuration with an average overprediction of 1.1. The average overprediction is 1.4 and 1.6 for the U and R channels, respectively.

Table 5. Ship and channel input parameters for EM 1110-2-1613 Panamax tanker.							
L_{pp} (m)	B (m)	T (m)	C_B	h (m)	h_T (m)	W (m)	n
209.7	32.3	12.2	0.85	13.4	7.32	91.4	3
Notes: Tfp = Tap = T; IProp = 1; IBow = 1; IStern = 0; KpS = 0.15; KpT = 0.15.							

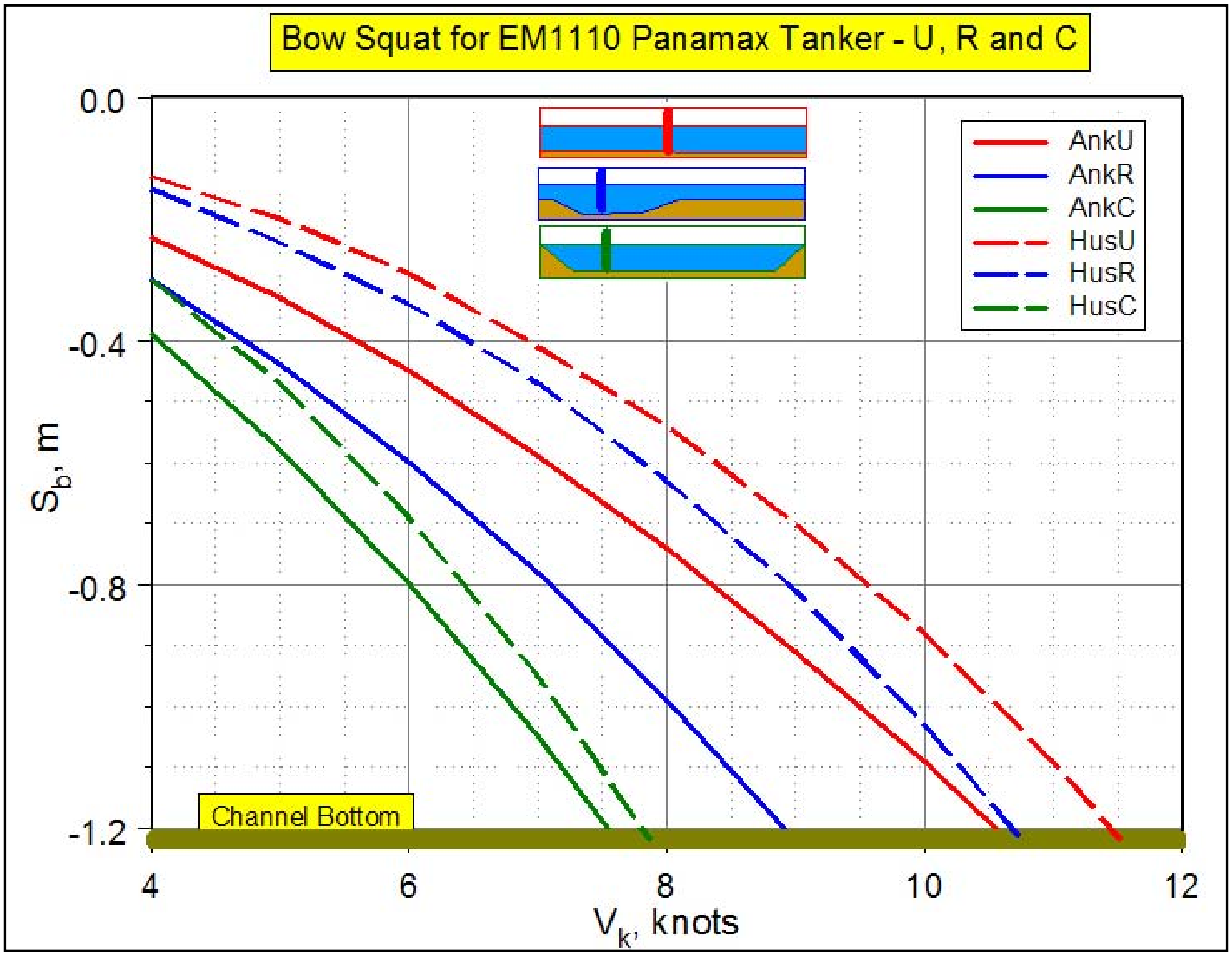

Figure 5. Ankudinov bow squat predictions for EM 1110-2-1613 Panamax tanker in U, R, and C channels.

Table 6. Statistical ratios of Ankudinov to Huuska bow predictions for EM 110-2-1613 Panamax tanker.			
Statistic	**Channel Type**		
	Unrestricted U	**Restricted R**	**Canal C**
Minimum	1.1	1.3	0.9
Average	1.4	1.6	1.1
Maximum	1.8	2.0	1.3

SUMMARY: This technical note has documented the Ankudinov formulation for ship squat that was used in the ERDC Ship/Tow Simulator. Two FORTRAN computer programs were written: one for single ship speeds and one for multiple ship speeds. The theoretical formulation and ship and channel input and output parameters are described. An example with the modified *Bunga Saga Emphat* Panamax bulk carrier that was used in CETN-I-63 and CHETN-I-72 was presented to illustrate the input and output parameters and comparisons were made with the PIANC empirical squat formulas for bow and stern squat in unrestricted, restricted, and canal channels. Finally, another example for the EM 1110-2-1613 Panamax tanker was presented. In general, the Ankudinov formulas tend to overpredict bow and stern squat by factors of two and larger relative to the PIANC empirical formulas. The bow predictions were better (average overprediction of 1.5) than the stern predictions, which is good since both example ships would experience maximum squat by the bow. The PIANC predictions are not perfect, but are generally accepted by the port and harbor community as reasonable predictions of ship squat. In Part II of this CHETN, further comparisons and validations with laboratory and field measurements are presented and discussed.

ADDITIONAL INFORMATION: This CHETN was prepared as part of the Deep Draft Navigation Research Program, Ship Simulations work unit, and was written by Dr. Michael J. Briggs (*Michael.J.Briggs@usace.army.mil*, voice: 601-634-2005, fax: 601-634-3433) of the Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center. This technical note should be cited as follows:

> Briggs, M. J. 2009. *Ankudinov ship squat predictions – Part I: Theory, parameters, and FORTRAN programs*. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-IX-19, Vicksburg, MS: U.S. Army Engineer Research and Development Center, *http://chl.erdc.usace.army.mil/chetn/*.

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Appendix A: List of Symbols in FORTRAN Programs ANKUDINOV4 and ANKUDINOVM4

Symbol		Units	Eq. No.	Description
Equation	Program			
B_{Tr}	BTr	---		Stern transom width used in KTrT
F_{nh}	Fnh	---	6	Depth Froude Number
K_b^T	KbT	---	15	Bulbous bow factor
K_p^S	KpS	---	3	Propeller sinkage factor
K_p^T	KpT	---	14	Propeller trim factor
K_{Tr}	KTr	---	12	Trim coefficient
K_{Tr}^T	KTrT	---	16	Stern transom factor
K_{T1}^T	KT1T	---	17	Initial trim effect factor
n_{Tr}	nTr	---	13	Trim exponent
P_{Ch1}	P_Ch1	---	8	Channel effect parameter
P_{Ch2}	P_Ch2	---	18	Channel effect trim correction parameter
P_{Fnh}	Par_Fnh	---	5	Ship forward speed parameter
P_{hT}	Par_hT_s	---	11	Propeller effect in shallow water on trim parameter
$P_{+h/T}$	Par_hT	---	7	Water depth parameter
P_{Hu}	Par_Hull_s	---	4	Ship hull parameter for shallow water
S_b	SbA	m	1	Ship squat at bow
S_h	Sh	---	9	Channel depth factor for R and C channels
S_m	SMid	m/m	2	Midpoint ship sinkage
S_s	SsA	m	1	Ship squat at stern
$Trim$	Trim	m/m	10	Ship trim

Notes:
1. Input symbols are defined in Table 1.